Advanced Mirror Technology Development (AMTD) Project: Overview and Year 4 Accomplishments

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AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

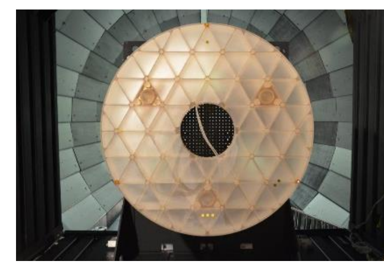
SPIE Conference on Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, 2016

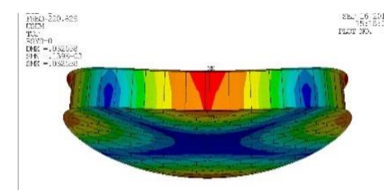
Accomplishments since Tech Days 2015

- Continuing Science Driven Systems Engineering: deriving Telescope Stability Requirements for Coronagraph 10^{-10} Contrast Leakage.
- Harris Corp fused and slumped 1.5-meter ULE© mirror which is currently in polishing. (Scheduled for cryo-test in Mar/Apr)
- Schott polished 1.2 m Zerodur® mirror which has been cryo & mechanical tested for model validation.
- Using Arnold Mirror Modeler to perform HabEx 4-meter mirror trade studies.
- 4 Student Interns
- 8 Publications
- Predictive Thermal Control for Stable Telescopes

Segments		WFE (pm)
	Piston	10
	Tip / Tilt	20
	Power	30
	Astigmatism	35
	Trefoil	65
Global		
	Power	3000
	Coma	5800
	Spherical	500
	Back Plane Bend	500

Courtesy of Harris Corp





Recent Publications

Stahl, H. Philip, “Advanced mirror technology development (AMTD) project: overview and year four accomplishments,” Proc. SPIE 9912, Advances in Optical and Mechanical Technology for Telescopes and Instrumentation II, (August 2016); doi: 10.1117/12.2234082.

Stahl, H. Philip, “Overview and accomplishments of advanced mirror technology development phase 2 (AMTD-2) project”, Proc. SPIE. 9602, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VII, 960208. (September 22, 2015) doi: 10.1117/12.2186195.

Stahl, Mark T., H. Philip Stahl, and Stuart B. Shaklan “Preliminary analysis of effect of random segment errors on coronagraph performance”, Proc. SPIE. 9605, Techniques and Instrumentation for Detection of Exoplanets VII, 96050P. (September 24, 2015) doi: 10.1117/12.2190160.

Arnold, William R, “Recent updates to the Arnold Mirror Modeler and integration into the evolving NASA overall design system for large space-based optical systems” Proc. SPIE. 9573, Optomechanical Engineering 2015, 95730H. (September 02, 2015) doi: 10.1117/12.2188750

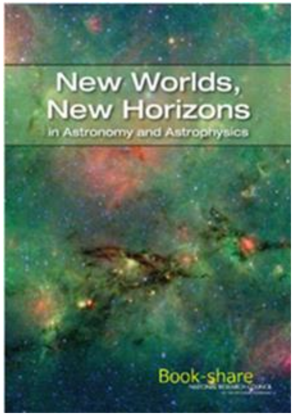
Arnold, William R. “Evolving design criteria for very large aperture space-based telescopes and their influence on the need for intergrated tools in the optimization process”, Proc. SPIE. 9573, Optomechanical Engineering 2015, 95730G. (September 02, 2015) doi: 10.1117/12.2188570

Brooks, Thomas, H. P. Stahl, William R. Arnold, “Advanced Mirror Technology Development (AMTD) thermal trade studies”, Proc. SPIE. 9577, Optical Modeling and Performance Predictions VII, 957703. (September 23, 2015) doi: 10.1117/12.2188371

Egerman, et. al., “Status of the Advanced Mirror Technology Development (AMTD) phase 2 1.5m ULE mirror”, Proc. SPIE. 9575, Optical Manufacturing and Testing XI, 95750L. (August 27, 2015) doi: 10.1117/12.2188566

Knight, J. B., “AMTD: Advanced Mirror Technology Development in mechanical stability” Proc. SPIE. 9577, Optical Modeling and Performance Predictions VII, 957704. (September 23, 2015) doi: 10.1117/12.2189312

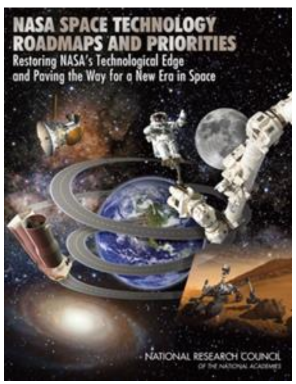
AMTD driven by NASA's need for Mirror Technology



Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

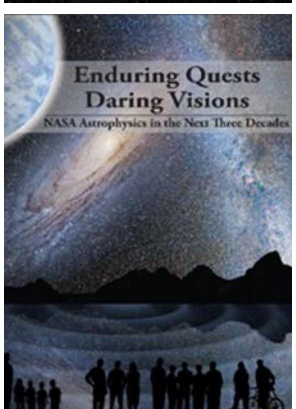
Exoplanet Mission (New-Worlds Explorer)

UVOIR Space Telescope (4 meter or larger)



2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …



2014 Enduring Quests Daring Visions recommended:

8 to 16-m LUVOIR Surveyor with sensitivity and angular resolution to "dramatically enhance detection of Earth-sized planets to statistically significant numbers, and allow in-depth spectroscopic characterization."

Objective

AMTD's objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

AMTD is not developing technology for a specific mission.

AMTD technology is relevant for high-contrast imaging & spectroscopy architectures:

single aperture monolithic mirror telescope - HabEx,
single aperture segmented mirror telescope – LUVOIR,
sparse aperture, and
interferometers.

Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide the science community with options, we are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

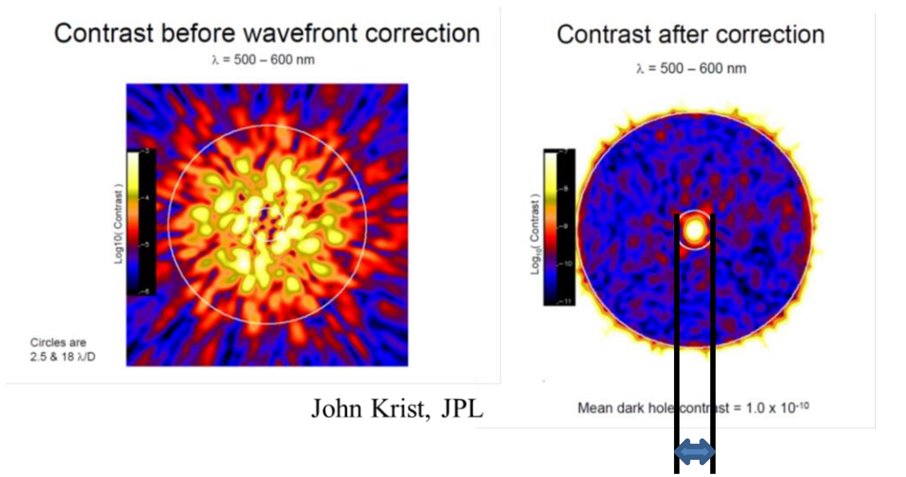
All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

Very Smooth Surfaces	< 10 nm rms
Thermal Stability	Low CTE Material
Mechanical Stability	High Stiffness Mirror Substrates

‘The’ System Challenge: Dark Hole

Imaging an exoplanet, requires blocking 10^{10} of host star’s light

An internal coronagraph (with deformable mirrors) can create a ‘dark hole’ with < 10^{-10} contrast.



John Krist, JPL

Inner Working Angle

Ultra-smooth, Ultra-Stable Mirror Systems are critical to achieving and maintaining the ‘dark hole’

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

Shaklan, Green and Palacios, “TPFC Optical Surface Requirements”, SPIE 626511-12, 2006.

Technical Approach/Methodology

To accomplish our objective, we:

- Use a science-driven systems engineering approach.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Phase 1 & 2

Goals, Objectives & Tasks

Goals

To accomplish Objective, must mature 6 linked technologies:

Large-Aperture, Low Areal Density, High Stiffness Mirrors: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.

Support System: Large-aperture mirrors require large support systems to ensure that they survive launch & deploy on orbit in a stress-free & undistorted shape.

Mid/High Spatial Frequency Figure Error: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.

Segment Edges: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.

Segment-to-Segment Gap Phasing: Segment phasing is critical for producing a high-quality temporally stable PSF.

Integrated Model Validation: On-orbit performance is determined by mechanical & thermal stability. Future systems require validated models.

Technical Approach/Methodology

We mature these technologies simultaneously because all are required to make a primary mirror assembly (PMA); AND, it is the PMA’s on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.

Phase 1: Goals, Progress & Accomplishments

Key
Done
Stopped
In-Process
Not Started Yet

Systems Engineering:

- **derive from science requirements monolithic mirror specifications**
- **derive from science requirements segmented mirror specifications**

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- **make a subsection mirror via a process traceable to 500 mm deep mirrors**

Support System:

- **produce pre-Phase-A point designs for candidate primary mirror architectures;**
- **demonstrate specific actuation and vibration isolation mechanisms**

Mid/High Spatial Frequency Figure Error:

- **'null' polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.**

Segment Edges:

- **demonstrate an achromatic edge apodization mask**

Segment to Segment Gap Phasing:

- **develop models for segmented primary mirror performance; and**
- **test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.**

Integrated Model Validation:

- **validate thermal model by testing the AMSD and deep core mirrors at 2°C**
- **validate mechanical models by static load test.**

Phase 1: Key Accomplishments

- Derived from Science Requirements, Specifications for Primary Mirror Wavefront Error and Stability
  - Surface < 10 nm rms (low ~5 nm, mid ~5 nm, high ~3 nm)
  - Stability < 10 picometers rms per 10 minutes
- Demonstrated, at the 0.5-m scale, the ability to make mechanically stiff, i.e. stable, UVOIR traceable mirrors:
  - <6 nm rms surface
  - 60-kg/m2
  - 400-mm deep-core substrate

using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process.

- Developed Tools for Integrated Modeling & Verification

Phase 2: Tasks

Refine engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 4 inter-linked critical technologies.

Large-Aperture, Low Areal Density, High Stiffness Mirrors

Fabricate a 1/3rd scale model of a 4-m class 400 mm thick deep-core ULE© mirror – to demo lateral scaling.

Support System – **continue Phase A design studies**

Mid/High Spatial Frequency Figure Error

Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

Integrated Model Validation – **continue developing and validating tools**

Phase 2: Tasks

Key
Done
Stopped
In-Process
Not Started Yet

Monolithic Mirror Substrate Technology

- Fabricate and test A-Basis allowable required for mirror
- Design 1/3-scale model of a 4-m x 400-mm class ~150Hz ULE® mirror
- Design support structure for Zerodur 1.2m mirror

Mirror Preparation

- Fabricate & polish 1/3-scale model ULE mirror & support structure
- Fabricate support structure & Polish Zerodur mirror

Thermal Characterization

- "Qualify" (i.e., test) two candidate lightweight primary mirrors (1.5m Harris & 1.2m Zerodur Schott) in X-Ray & Cryogenic Facility at MSFC
  - Characterize their optical performance from 230K to ambient

Expose to representative vibration and acoustic launch environments & conduct modal test of 1.5m Harris & 1.2m Zerodur Schott

Summary of Following Presentations

- AMTD Phase 2 Status of ULE® Mirror
  - Review accomplishments, lessons learned & status of 1.5 m mirror which is currently in polishing and schedule for testing in March 2017.
- AMTD Test Results of Schott 1.2m ELZM mirror
  - Present cryogenic and mechanical test results of the Schott 1.2 m extreme-lightweight Zerodur© mirror
- Schott ELZM mirror thermal model predictions and test data correlation.
- Arnold Mirror Modeler status and use on 4-meter point design trade study for HabEx
- Update on derive Systems Specifications for Telescope WFE Stability based on Coronagraph Contrast Leakage
- Predictive Thermal Control SAT Goals and Objectives

Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Demonstrated capability of 'stack & seal' process:

- Make 40-cm deep mirrors
- Lateral scalability to 1.5-m diameter
- Validated Non-Linear Visco-Elastic Modeling

Continuing improvement of Arnold Mirror Modeler for rapid design of mirror substrates and support systems to enable point design trade studies.

Developing integrated modeling methods to derive engineering specifications from science requirements.

Validate by Test Integrated Model Performance Predictions.